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Impacts of unpaved roads on runoff and erosion in a dry tropical setting: Isla De Culebra, Puerto Rico

C. E. Ramos-Scharrón[1,2] · P. McLaughlin[1] · Y. Figueroa-Sánchez[3]

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Abstract

Purpose Unpaved road erosion represents a key source of terrigenous sediment threatening Caribbean coral reefs, yet no empirical data existed to document this in Culebra, Puerto Rico. Here, we compared unpaved road erosion to that from undisturbed hillslopes and evaluated the effects of road grading frequency and slope on erosion.

Methods A total of 46 plot-scale rainfall simulation experiments were used to measure runoff response and erosion rates from undisturbed hillslopes and unpaved roads with varying slopes and time since grading. Rainfall rates recorded over a one-year period combined with empirically derived infiltration capacity curves and erosion rates allowed for annualizing runoff and sediment production for natural hillslopes and four road types representing different grading frequencies and slopes.

Results Infiltration rates from roads were between a tenth and a quarter of those from natural hillslopes and that lead to roads generating runoff five times more frequently than natural hillslopes annually. Road erosion rates were between 330 and 760 times greater than those from undisturbed hillslopes, depending on slope and grading. Roads represent a dominant source of sediments responsible for increasing watershed-scale erosion rates from 1.1 to 25 times above background rates.

Conclusion Unpaved roads represent a major source of the sediment that threatens the coral reefs of Culebra. Therefore, future new road building must be kept to a minimum and unpaved roads must be the focus of coral reef protection efforts.

Keywords Unsurfaced roads · Coral reefs · Sediment · Caribbean

1 Introduction

The worldwide decline in live coral cover over the past few decades is likely a product of regional pressures (e.g., warmer sea surface temperatures and subsequent bleaching/disease), yet local stressors (e.g., overfishing, land-based sources of pollution) are of concern as these are viewed as vital in defining coral reef resilience (Souter et al. 2021; Virgen-Urcelay and Donner 2023). This is particularly true in the Caribbean, where bleaching events in 1998 and 2005 followed by widespread diseases caused a major drop in coral cover (Cróquer and Weil 2009; Goreau et al. 1998; Miller et al. 2009), but also where land development and its effects on water quality are still believed to have an unequivocal detrimental effect on coral reefs (Cramer et al. 2020; Suchley and Alvarez-Filip 2018). Although we still lack rigorous long-term studies of the effects of exposure to terrestrial sediments on live coral cover and coral reef composition (Jackson et al. 2014; Rogers and Ramos Scharrón 2022), terrestrial sediments are believed to be a main source of marine water pollution and coral stress throughout the Caribbean (Restrepo et al. 2016; Roberts et al. 2017).

Coral reefs of the Puerto Rican archipelago have displayed the same adverse effects of bleaching and disease incidence as those reported throughout the Caribbean (Weil et al. 2009; Winter et al. 1998) while also being exposed to the pressures of impoverished water quality due to land development (Hernández-Delgado et al.

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✉ C. E. Ramos-Scharrón
cramos@austin.utexas.edu

1 Department of Geography and the Environment, The University of Texas at Austin, Austin, TX, USA

2 Lozano Long Institute of Latin American Studies, The University of Texas at Austin, Austin, TX, USA

3 Protectores de Cuencas Inc., Yauco, Puerto Rico

2012). In Puerto Rico (PR), terrestrial sediments are considered a major threat to corals (Ballantine et al. 2008; Larsen and Webb 2009), and many management plans are devoted to reduce terrestrial sediment loading into coral reef ecosystems (Carriger et al. 2013; Sturm et al. 2014). Shallow landslides provoked during high intensity rain events are a main source of terrestrial sediment throughout the wet tropical areas of PR (Irizarri Brugman et al. 2021; Larsen 2012), yet agricultural land, and unpaved roads within farms in particular, are also key sources of sediment (Ramos Scharrón and Thomaz 2017) that have become a key target for management plans (Gibbs et al. 2021; Sturm et al. 2012).

The island-municipality of Culebra supports coral reef ecosystems that are characteristic of the northeastern Caribbean marine biodiversity (Hernandez-Delgado et al. 2000) and represent valuable sources of fishing, tourism, and recreational activities (Montañez Acuña 2022). Culebra is home to the first no-take natural reserve in PR, the Canal Luis Peña Natural Reserve (CLPNR) (Pagán-Villegas et al. 1999), in addition to housing various coral reef and reef fisheries management conservation efforts (Hernández-Delgado et al. 2018) including those targeting terrestrial sediments (Viqueira Ríos et al. 2016). A wave of land development that began to take hold of Culebra in the 1990s raised concerns on its potential adverse impacts on nearshore marine ecosystems due to increased terrestrial sediment loading (Collazo et al. 1992; Hernández-Delgado 1992). Landslides are mostly absent in the dry tropical and relatively subjugated topography landscape of Culebra, and similar to other coastal dry tropical settings of the region, unpaved roads are the main source of sediments reaching coastal waters (Bégin et al. 2014; MacDonald et al. 1997; Nemeth and Nowlis 2001). Previous work conducted in nearby dry tropical areas has shown that the relative impact of unpaved roads depends on background runoff and erosion rates, rainfall patterns, road grading frequency, and road slope (Ramos Scharrón et al. 2023).

Even though previous unpaved road erosion modeling work has been conducted in Culebra (Ramos Scharrón et al. 2012), the present work represents the first empirical documentation of the effects of unpaved roads in altering runoff and sediment generation on the island. The specific objectives of this article are to: (1) rely on experimental data to generate infiltration capacity curves and to calculate average surface erosion rates for undisturbed hillslopes and unpaved roads under varying grading frequency regimes and slopes and (2) calculate per unit area annualized runoff amounts and erosion rates for undisturbed hillslopes and roads and compare those with values published in the literature for other dry tropical areas in the Caribbean.

2 Methods

2.1 Study area

Culebra lies ~28 km east of mainland PR and consist of a 26.6 km^2 major land mass and 20 cays. Culebra lies within the PR-Virgin Islands microplate, an active deformation zone between the Caribbean and Atlantic plates (Jansma et al. 2000). Culebra has a maximum elevation of just shy of 200 m with slopes averaging 28%. The island's vegetation is sub-tropical dry, typical where annual rainfall rates are low relative to evapotranspiration potential (Ewel and Whitmore 1973). About 45% of the island is covered with lowland dry shrubland and woodland, 27% is lowland dry semideciduous forest, 14% is dry grasslands, 2% is mangroves and only 3% is developed (Gould et al. 2008). Watersheds within Culebra do not exceed 3 km^2 in drainage area and mostly are drained by ephemeral streams.

Historical land uses in Culebra are surprisingly varied given its small size and location relative to mainland PR. These uses include having served as the site for live ammunition training for the US Navy's Atlantic Fleet (1901–1978), hosting the first wildlife refuge of the entire Insular Caribbean (Culebra National Wildlife refuge established in 1909), and becoming a tourism hub from the 1990s onward. The main natural resource attractions in Culebra are its internationally acclaimed white sand beaches, its resident population of green turtles feeding from the island's seagrass beds, and its coral reefs. However, increases in soil erosion caused by the relatively recent land development surge and the accompanying extension of the unpaved road network have increased terrigenous sediment loading to Culebra's coral reefs and associated habitats (Gómez-Andújar and Hernandez-Delgado 2020; Otaño-Cruz et al. 2017, 2019). Roads are mostly used by light vehicles accessing individual home properties with only occasional usage by heavier vehicles mostly during homesite construction. Unpaved road densities in Culebra's watersheds range from the low to the moderate with values from 0.7 to 6.4 km km^{-2} (Ramos Scharrón et al. 2012). Assuming an average road tread width of 5 m, these densities imply that roads occupy between 0.3 and 3.2% of these watersheds. Most roads are built and maintained without any stormwater or erosion control provisions even though new optional guidelines have been developed (Kitchell et al. 2021). Culebra is a priority coral reef protection site for the Commonwealth of Puerto Rico (PR-Commonwealth and NOAA-CRCP 2010), and it represents a location where watershed restoration actions targeting unpaved roads and other sources of pollution have been implemented (Viqueira Ríos et al. 2016).

2.2 Rainfall simulation experiments and statistical analyses

A total of 46 rainfall simulations were conducted in three distinct areas of Culebra (Fig. 1a). All of three areas share the same lithological and soil substrates (i.e., augite andesitic lavas and well-drained clay loams of the Descalabrado soil series) (Banks 1962; Soil-Survey-Staff Undated), topographic relief characteristics, and annual rainfall (~ 1160 mm yr^{-1}; Daly et al. (2003)). Experiments were conducted using a standardized rainfall simulator design (Luk et al. 1986) and bounded plots delimited by ~ 2.5-cm-thick iron plates vertically pounded into the soil (Fig. 1b–g). Field-measured plot surface areas and slopes were between 2.1 and 4.0 m^2 and 2–40%, respectively (Supplementary Materials A.1). Rainfall application during the experiments lasted between 60 and 225 min. The longest experiments were for undisturbed hillslopes as it took more than the standard 60 min for any runoff to be generated from them. Rainfall was measured every 5 min as the arithmetic average of readings from 6 manual rain gauges placed along the periphery of each plot. Experimental rainfall intensities were in the 30 to 70 mm hr^{-1} range (48 mm hr^{-1} average), which represent 1-h rain rates expected to occur in Culebra between once a year to once every 25 years, respectively (every 5 years for the average value) (Bonnin et al. 2006).

Experimental surfaces were classified based on a two-tier organization system for the purposes of site selection and analyses. Tier-1 simply classifies plots into natural hillslopes (NAT) and either ungraded or graded roads. Natural hillslopes sites were a combination of shrubland and grassland. Road surfaces that were last graded within two years of the experiments were categorized as graded (GR), while those that were not were labelled as ungraded (UG) following previous road erosion work in nearby St. John-US Virgin Islands (Ramos Scharrón and MacDonald 2007). Tier-2 further divides the two road surface types by slope using 20% as the cutoff for low-to-moderate (LM) and steep (S) types. Therefore, the study design relied on the following five surface types: natural hillslopes (NAT), ungraded roads with low-moderate slopes (UG-LM) and those with steep slopes (UG-S), and graded roads with low-moderate (GR-LM) and steep slopes (GR-S).

2.2.1 Runoff analyses

Runoff rates were measured at every 1-min interval in m^3 s^{-1} as the rate of runoff exiting each plot over a 5- to 15-s period. The ratio of total runoff to net average rainfall determined the runoff coefficient (R.C.) of each experiment. Comparisons of average R.C. values among the five different surface types were based on ANOVA and Tukey's Honest Significance Difference tests after testing for normal distribution following the Shapiro-Wilk test (Zar 1999).

For every experiment, differences between rain intensity averages ($\overline{R_t}$) and 1-min discharge rates (Q_t) were used to calculate intra-storm infiltration capacities (I_t) (all in mm hr^{-1}) as shown in Eq. (1):

$$I_t = \overline{R_t} - Q_t \tag{1}$$

I_t values during the last 15 min of each simulation were averaged based on each of the five plot types as the final infiltration rate ($\overline{I_f}$). $\overline{I_f}$ values for all group types were compared based on ANOVA and Tukey's HSD tests after being tested for normal distribution based on the Shapiro-Wilk test (Zar 1999). Results for individual experimental plots were averaged over every 1-min time step based on statistically different Tier-2 groupings to obtain a combined infiltration capacity curve for each statistically distinct surface type.

Infiltration capacities for road plots were modeled similarly to previous road runoff studies (Ramos Scharrón and LaFevor 2016; Ziegler and Giambelluca 1997) following the equation developed by Loague and Freeze (1985):

$$\hat{I}_t = \frac{1}{2} \times \left[S \times t^{-1/2} + K_{sat}\right] \tag{2}$$

where $\hat{I}_t$ is predicted infiltration capacity (in mm hr^{-1}) at time t in hours, S is sorptivity or the soil's ability to absorb water through capillary tension (in mm h$^{-1/2}$), and K_{sat} is saturated hydraulic conductivity in mm hr^{-1}. The two parameters in Eq. (2) were manually fitted to the average infiltration capacity curve for every unique surface type following both a graphical calibration approach and by seeking to maximize the model efficiency coefficient (Nash and Sutcliffe's coefficient or NS-R^2) (Nash and Sutcliffe 1970). Given the shape of the empirically derived infiltration capacity curve for undisturbed hillslopes, it was not possible to fit the model to these data, and we had to recur to other more informal approaches as it will be discussed later.

2.2.2 Erosion analyses

The same two-tier system used to analyze R.C. and $\overline{I_f}$ was used to evaluate differences in mean erosion rates ($\overline{E_r}$) among the five different surface types. During every experiment, runoff samples were collected in 0.5-L plastic bottles from the outlet of the collection trough at the onset of overland flow and at every 5-min interval as described by Ramos Scharrón and Thomaz (2017). Samples were analyzed for suspended sediment concentration based on the evaporation method (ASTM 2000). The combination of observed runoff rates, suspended sediment concentration, plot surface area, and rainfall allowed for the calculation of intra-storm sediment loss rates (in g min^{-1}) and area-rain normalized

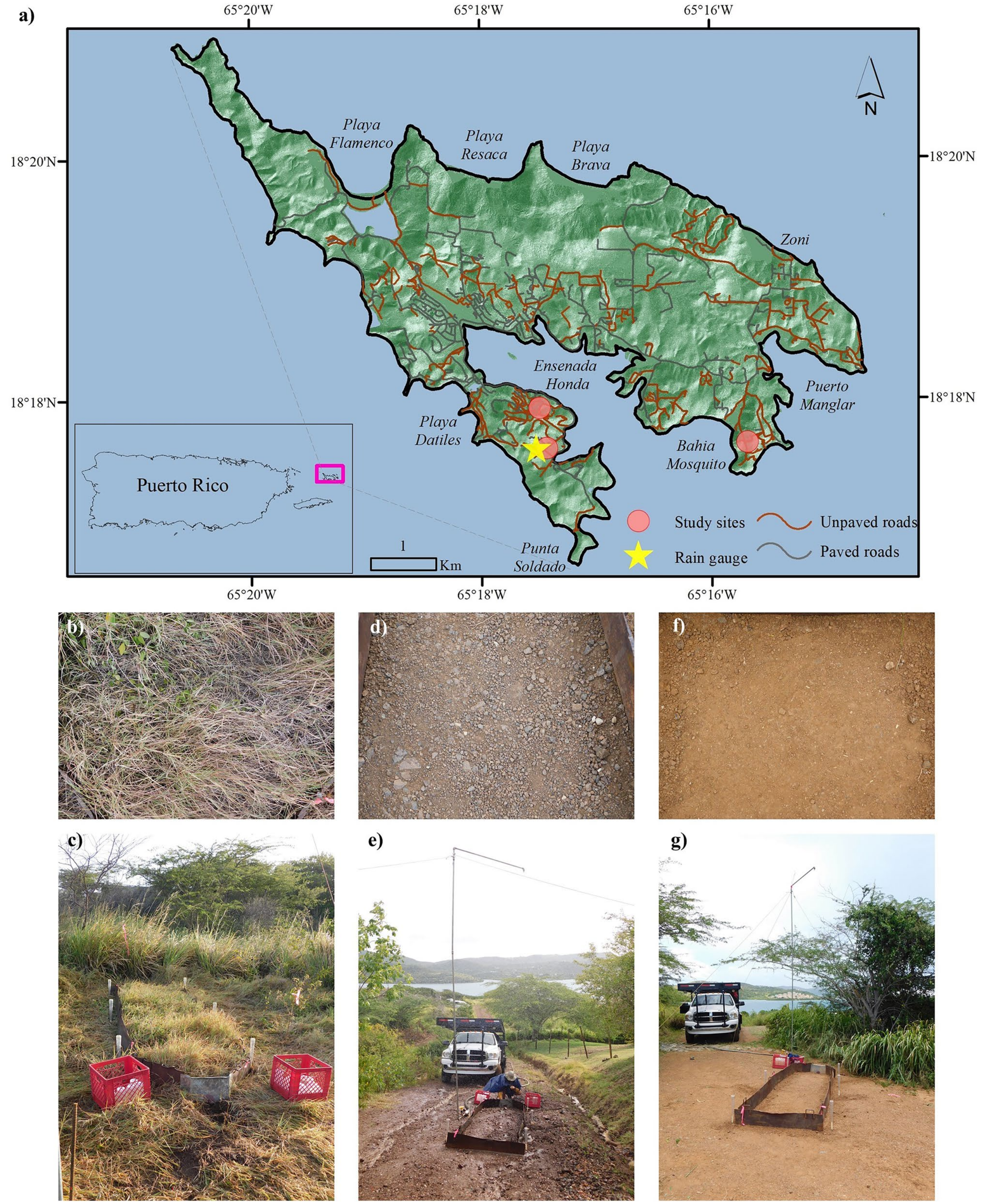

Fig. 1 The island of Culebra and study areas. **a** Map of Culebra displaying the general location of the rainfall simulation study sites, the rain gauge, and roads; **b**, **c** A natural hillslope surface and plot; **d**, **e** An ungraded road surface and plot; **f**, **g** A graded road surface and plot

erosion rates (E_r in g m^{-2} mm^{-1}) for every minute of each experiment. There is an important difference in how area-rain normalized average erosion rates for the five surface types were tested relative to R.C. and infiltration. The difference is that erosion analyses relied on intra-storm erosion rates (in g m^{-2} mm^{-1}) for every 1-min time step for which runoff was measured, while rainfall was occurring instead of relying on experiment-by-experiment average values. This allowed for a significantly larger sample size ($n=2259$ vs $n=46$) and thus improved statistical power. As for hydrologic analyses, differences in mean erosion rates were tested based on one-way ANOVA and Tukey's post hoc HSD tests after being evaluated for normality using the Shapiro-Wilk test. A single average area-rainfall normalized erosion rate ($\overline{E_r}$) was calculated for every surface identified as unique from an erosion rate perspective.

2.3 Annualized runoff and erosion rates

Storm-by-storm runoff was estimated for natural and road surfaces based on the difference between recorded rainfall rates and infiltration capacity curves. Rainfall rates in Culebra were measured from Aug. 17 to Jul. 18 by a recording rain gauge in the Punta Aloe area (Fig. 1a). In combination with the minute-by-minute estimated runoff rates, $\overline{E_r}$ values for each unique erosion surface type were used to estimate storm-by-storm and annualized sediment losses in Mg ha^{-1} yr^{-1}. Erosion totals (in g m^{-2}) for every storm were calculated by summing the product of minute-by-minute rainfall total (in mm) times the average rain and area normalized erosion rate for each surface type ($\overline{E_r}$ in g m^{-2} mm^{-1}) only for those 1-min periods for which precipitation excess was estimated. Annualized rates were compared to those reported in the literature for dry tropical areas.

3 Results and discussion

3.1 Runoff

On average ~70 min and ~65 mm of rain at a rate of ~55 mm hr^{-1} were needed to generate any runoff from natural hillslopes (Fig. 2a). Runoff rates from natural hillslopes stabilized at roughly 20–30% of rainfall rates about 210 min into the experiments. In contrast, road runoff began 2–4 min into the experiment and after only ~2 mm of rainfall at rain intensities of 35–50 mm hr^{-1} range. Road runoff rates stabilized at 70–100% of rain rates ~25 min into the experiments. Runoff coefficients for natural hillslopes averaged only 3% and were statistically different from the 66–88% range of average coefficients for all four road types (Fig. 2b). Runoff coefficients for roads with low and moderate slopes were generally lower than those for steep roads although the differences were not all statistically significant. Grading did not prove to have any impact on runoff coefficients even though grading activities were performed by heavy machinery that included compaction with a 15-Ton roller.

The infiltration rate curve for natural hillslopes displayed a different behavior than that which could be modeled by Eq. (2). This is because values remained high for a relatively long period before they exponentially dropped and asymptotically approached saturated levels. Given the shape of the resulting infiltration curve for natural hillslopes, we recurred to modeling infiltration capacities assuming a constant value of 55.8 mm hr^{-1} during the first 175 min of rainfall and a value of 33.5 mm hr^{-1} for times beyond 225 min. The 33.5 mm hr^{-1} value is very similar to the empirically-derived average K_{sat} value of 36.2 mm hr^{-1} for undisturbed soils in Culebra determined with a Guelph permeameter (McLaughlin 2019). For the transition period between 176 and 225 min, we relied on an exponential curve determined by regression analyses to estimate the decline in infiltration capacities ($R^2=0.56$; Fig. 3a). In contrast to natural hillslopes, infiltration rates for roads were 35–54 mm hr^{-1} early during the rainfall simulations and dropped to 3.5–10.6 mm hr^{-1} during the last 15 min of the experiments (Fig. 2c–d). The highest $\overline{I_f}$ values were for low and moderate sloped roads. However, neither the effects of road grading nor slope proved to have a statistically consistent effect on infiltration rates. Therefore, data for all roads regardless of type was used in calibrating Eq. (2) for which we settled on 12 mm $hr^{-1/2}$ and 8 mm hr^{-1} for S and K_{sat}, respectively (Fig. 3b). Infiltration capacity and K_{sat} values for roads in Culebra are within the range of values reported in the literature for roads in different parts of the world (~0.0–3.6 mm hr^{-1} range) (Kastridis 2020; Ziegler et al. 2007) including the dry tropics (~6-mm hr^{-1} range; Ramos Scharrón et al. (2023)).

3.2 Erosion

Intra-storm $\overline{E_r}$ on natural hillslopes averaged 0.02 g m^{-2} mm^{-1} and ranged from 0.0005 to 0.14 g m^{-2} mm^{-1} (Fig. 2e–f). In contrast, road $\overline{E_r}$ values were 75–170 times greater depending on time since grading and slope with values ranging from 0.07 to 10.5 g m^{-2} mm^{-1}. Results show that both road grading and slope had an effect on erosion rates as average values for each of the four road types were statistically different from all others. The effects of grading and slope on road $\overline{E_r}$ were interrelated as has been noted for unpaved roads in both dry and wet tropical areas of PR (Ramos Scharrón et al. 2023). Grading increased erosion by 23% for roads with low-moderate slopes, while its effect was higher at 41% for steep roads. Increases from low–moderate to steep slopes increased erosion by 62% for ungraded roads, but slope differences amounted to an 85% increase in $\overline{E_r}$ for graded roads.

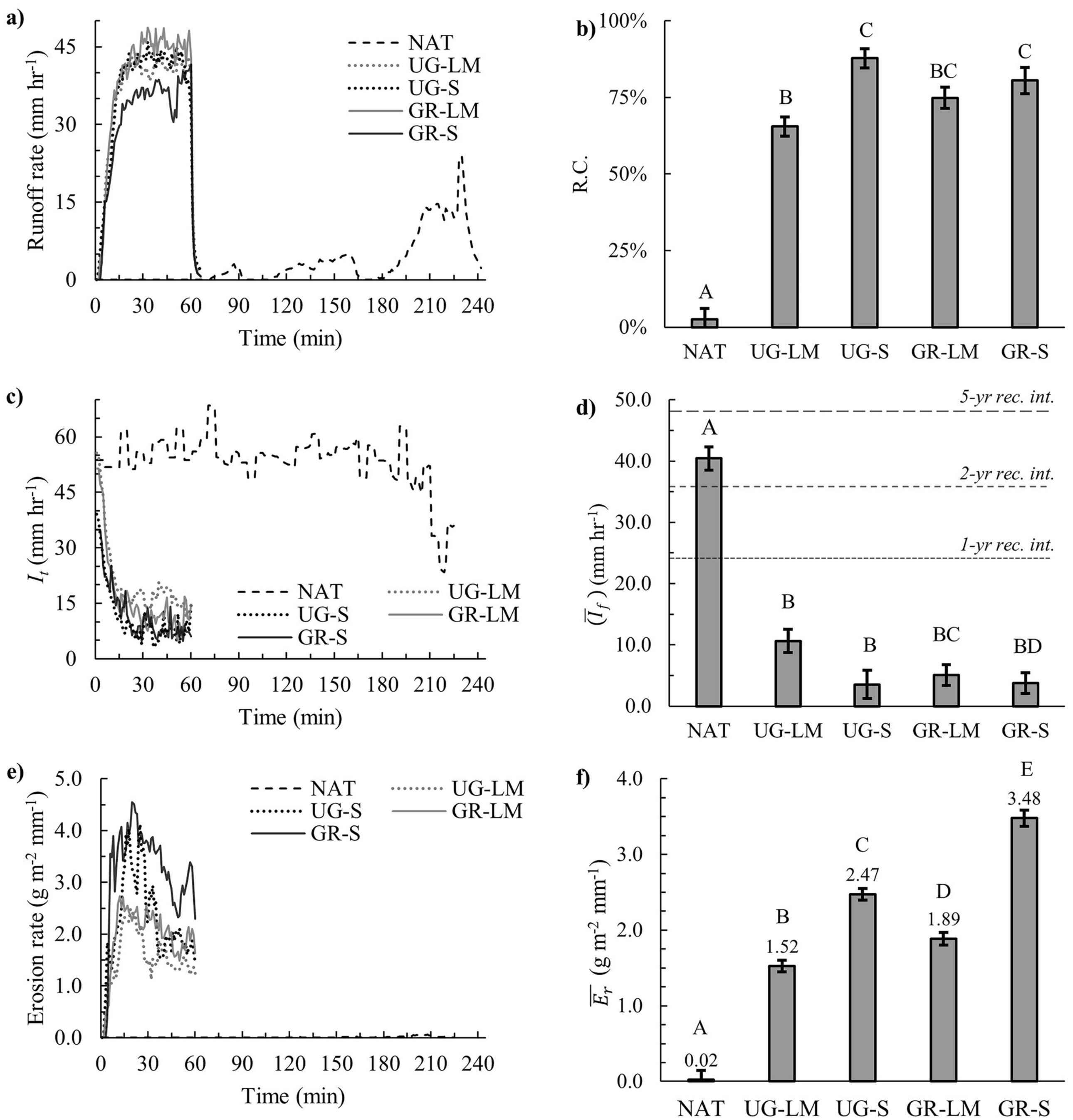

Fig. 2 Rainfall simulation results. **a** Runoff rates versus time since start of simulation. **b** Average runoff coefficients (R.C.). **c** Empirically derived infiltration rates versus simulation time. **d** Average final infiltration rates ($\overline{I_f}$) and 60-min rainfall intensities with 1-year, 2-year, and 5-year recurrence intervals according to Bonnin et al. (2006). **e** Average erosion rates versus simulation time. **f** Average erosion rates ($\overline{E_r}$). For graphs (**b**), (**d**), and (**f**), columns with different letters represent statistically significant differences in average values

3.3 Annualized runoff and erosion rates

Rainfall totaled 1289 mm between Aug. 2017 and Jul. 2018, and this is only 11% higher than the normal 30-year average. Observed rainfall occurred during 323 individual storms with individual sizes ranging from 0.2 to 97.5 mm (average of 4.0 mm) which included rain associated to Hurricanes Irma and María in Sept. 2017 (Supplementary Materials A.2). Five-minute natural rain intensities reached a maximum of 142 mm hr^{-1} and averaged 8.8 mm hr^{-1}. About 99% of all 5-min rainfall intensities were below those with an expected recurrence interval of 1 year (69 mm hr^{-1}), while

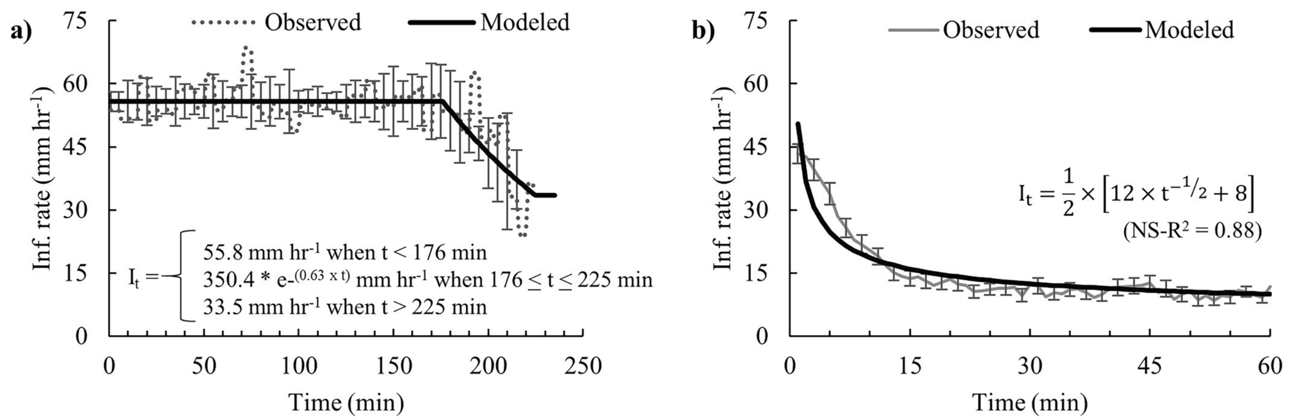

Fig. 3 Infiltration capacity models. **a** Natural hillslopes and **b** roads. NS-R^2 refers to the Nash-Sutcliffe efficiency coefficient

the maximum intensity recorded has a recurrence interval between 5 and 10 years (Bonnin et al. 2006).

Runoff from undisturbed hillslopes was estimated during only 18 of the 323 rain events (5.6%) and amounted to an overall runoff coefficient of 3.9%. In contrast, road runoff was expected during 90 or 28% of all the rain events and amounted to a runoff coefficient of 34% (Fig. 4a). Therefore, road surfaces are expected to generate runoff roughly five times more frequently than undisturbed hillslopes. Not all road runoff gets delivered to coastal waters as road-to-coast connectivity depends on road characteristics, the characteristics and distance between road drains and receiving water body, and storm size (Benda et al. 2019). However, it is important to note the frequency of road runoff occurrence estimated for Culebra (~ 40 times in one year) with the fact that under undisturbed conditions, ephemeral streams in this climatic regime deliver runoff to coastlines only ~ 4 times per year only when storms exceed ~ 10–78 mm of rainfall (Larson et al. 2015; Ramos Scharrón and LaFevor 2018).

Based on rainfall registered between Aug. 2017 and Jul. 2018, annual road erosion rates in Culebra range from 12 to 27 Mg ha^{-1} yr^{-1} depending on time since grading and slope. Differences in annual erosion rates among the four road types are the same as those documented for the simulation experiments given that our estimates relied on a singular infiltration capacity equation for all road types (Fig. 3b). Annualized road erosion rates for Culebra are on the mid-range of values reported for other dry tropical areas in the Caribbean (i.e., St. John-USVI and La Parguera and Cabo Rojo in Southwest PR) which average ~ 47 Mg ha^{-1} yr^{-1} (Ramos Scharrón et al. 2023), yet individually have reached up to 580 Mg ha^{-1} yr^{-1} (Ramos Scharrón and MacDonald 2007) (Fig. 5). Annualized road erosion rates in Culebra are between 330 and 760 times greater than natural erosion (~ 0.035 Mg ha^{-1} yr^{-1}). For other areas of the dry tropics,

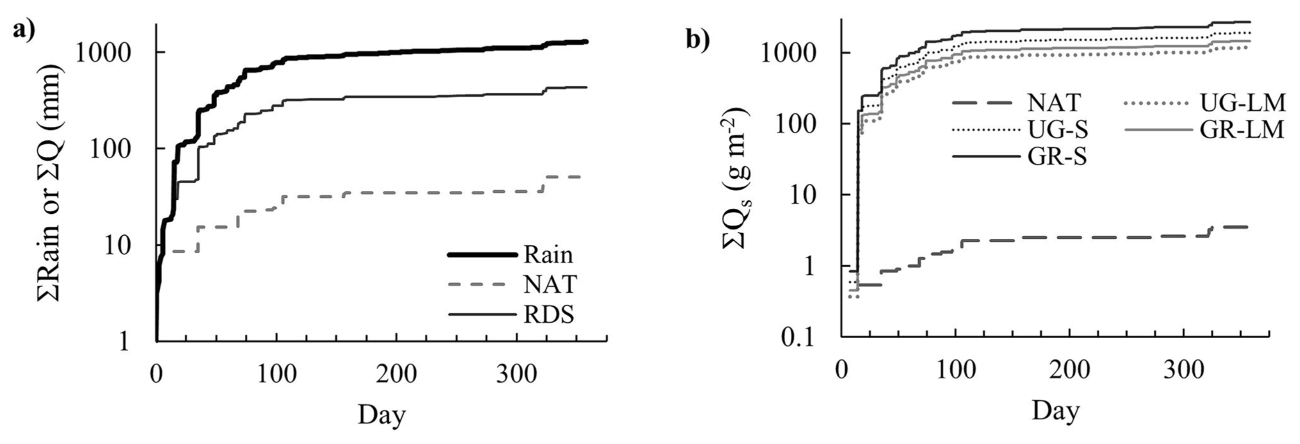

Fig. 4 Annualized cumulative rainfall and estimated runoff (**a**) and erosion (**b**) for natural hillslopes and roads. Day 0 represents 1 Aug. 2017. NAT refers to natural hillslopes; RDS refers to roads

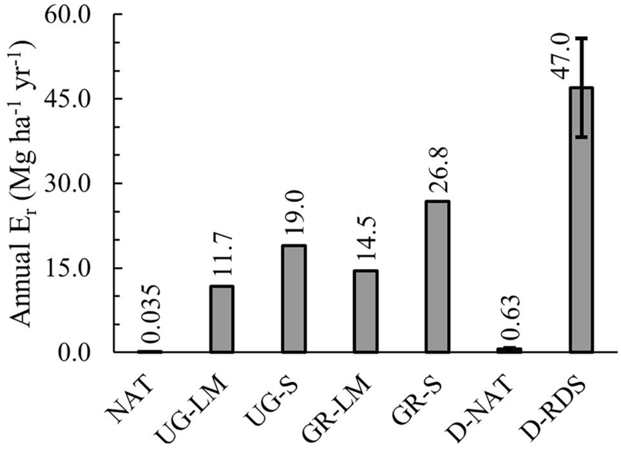

Fig. 5 Annual erosion rates estimated for natural hillslopes and unpaved roads in Culebra and for other dry tropical areas. Columns represent mean values and error bars represent standard errors. D-NAT and D-RDS refer to average natural and road erosion rates for dry tropical areas of the Caribbean as compiled by Ramos Scharrón et al. (2023)

annual unpaved road erosion it is about 75 times above background, although steep and frequently graded road segments (up to twice per year) have been shown to have a four-order of magnitude impact (Ramos Scharrón and MacDonald 2007). The overall higher impact of unpaved roads on erosion documented for Culebra is due to the island's lower natural erosion rates relative to other areas for which the annual average is more than one-order of magnitude greater (~0.63 Mg ha^{-1} yr^{-1}). The lower natural erosion rates may be due to higher vegetation density of the island's shrubland and grassland surfaces relative to patchier open woodland and thorn-and-cactus vegetation cover of previously documented sites in La Parguera-PR and eastern St. John and St. Croix in the USVI (respectively) (MacDonald et al. 2001; Ramos Scharrón et al. 2023).

3.4 Implications of study results

Our analyses show that it takes either an extremely long individual rainstorm (> 3 h) or presumably wet initial conditions for infiltration capacities of natural hillslopes to drop to rates that are within the range of commonly occurring rainfall intensities with recurrence intervals of less than 2 years (30–40 mm hr^{-1}) (Figs. 2d and 3a). This explains the paucity of predicted runoff on natural hillslopes. Between Aug. 2017 and Jul. 2018, only 18 of the 323 rain events observed in Culebra likely generated any excess precipitation runoff from natural hillslopes (Fig. 4a). In contrast, infiltration capacities of unpaved roads drop below 10–15 mm hr^{-1} only 15 min after the beginning of rainfall which is well within range of frequently occurring rain intensities (Figs. 2d and 3b), and this allows unpaved roads to generate runoff five times more frequently than undisturbed hillslopes (Fig. 4). The large discrepancy in infiltration capacities and runoff generating frequencies between natural hillslopes and unpaved roads have two important implications for watershed management. First, this confirms that roads can potentially increase the frequency of runoff and sediment delivery from watersheds to marine ecosystems as it has been shown in other tropical areas (Wemple et al. 2018), islands of the Caribbean (Nemeth and Nowlis 2001), and as was previously speculated in Culebra (Otaño-Cruz et al. 2017). Second is that the high infiltration rates of undisturbed hillslopes potentially can be used to impede road runoff delivery to coastlines by carefully managing road drainage and using hillslopes as buffer zones (Zhao et al. 2022). The results of this study will be integrated within a spatially explicit road runoff and sediment connectivity model (Ramos Scharrón 2021) that will allow mapping of road runoff delivery potential and evaluating the effects of management actions such as insloping, increasing road drain densities, and building of detention ponds to prevent road-to-coastline connectivity.

Annual road erosion rates in Culebra range from a low of 11.7 Mg ha^{-1} yr^{-1} for roads with less than 20% slopes that have not been graded for over two years, up to a high of 26.8 Mg ha^{-1} yr^{-1} for recently graded roads exceeding 20% in slope. Based on these values and considering that unpaved roads in Culebra occupy between 0.3% and 3.2% of the land surface, annual watershed-scale sediment production rates from roads on the island are between 0.04 and 0.86 Mg ha^{-1} yr^{-1} or 1.1 to 25 times greater than under undisturbed conditions (respectively). These values imply that for every 1% of a watershed occupied by roads, sediment production increases by three to almost eight times above background rates. These findings stress the high sensitivity of this landscape to land development in terms of erosion and potentially terrigenous sediment loading to coastal waters. Additionally, the results of this study highlight the importance of maintaining new unpaved road construction to an absolute minimum and prioritizing the existing road network as a target of watershed restoration activities to help Culebra's coral reef ecosystems maintain their resilience to both regional and local stressors.

4 Conclusions

Accelerated sediment production from unpaved roads are perceived as a major local threat for the coral reefs in the vicinity of the island of Culebra in Puerto Rico. This study relied on plot-scale rainfall simulation experiments to evaluate the effects of rainfall, road grading frequency, and slope on runoff generation and erosion. Results showed that roads have infiltration capacities in the 4–11 mm hr^{-1} range and that these are between a tenth and a quarter of those from undisturbed hillslopes. Comparisons between observed rainfall intensities and empirically derived infiltration capacity curves showed that road runoff can occur about five times more frequently than hillslope runoff, and this highlights the potential for roads to increase the frequency of sediment delivery to coastal waters in this ephemeral dry tropical system.

Road erosion rates were found to be controlled by road grading and slope. In Culebra, ungraded roads with low-moderate slopes of less than 20% erode at an annual rate of ~ 12 Mg ha^{-1} yr^{-1}. Erosion from steep roads graded at least once over the last two years is ~ 27 Mg ha^{-1} yr^{-1}. Therefore, road erosion rates are between 330 and 760 times greater than those from natural hillslopes. Given that roads on Culebra occupy 0.3–3.2% of the land surface, watersheds containing roads have sediment production rates of 0.04–0.86 Mg ha^{-1} yr^{-1}, and these are 1.1 to 25 times greater than under undisturbed conditions. The results of this study highlight the dominant role of unpaved roads as terrigenous sediment sources that can potentially affect coral reefs near Culebra and in other dry tropical areas.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11368-024-03749-2.

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Data Availability Derived data supporting the findings of this study are available from the corresponding author on request.

Declarations

Conflict of interest The authors declare no competing interests.

References

ASTM (2000) Standard test methods for determining sediment concentration in water samples. ASTM International

Ballantine DL, Appeldoorn RS, Yoshioka P, Weil E, Armstrong R, Garcia JR, Otero E, Pagan F, Sherman C, Hernandez-Delgado EA (2008) Biology and ecology of Puerto Rican coral reefs. Coral reefs of the USA. Springer, pp 375–406

Banks TH (1962) Geology of Culebra Island, Puerto Rico. Masters Thesis. Rice University

Bégin C, Brooks G, Larson RA, Dragićević S, Scharrón CER, Côté IM (2014) Increased sediment loads over coral reefs in Saint Lucia in relation to land use change in contributing watersheds. Ocean Coast Manage 95:35–45. https://doi.org/10.1016/j.ocecoaman.2014.03.018

Benda L, James C, Miller D, Andras K (2019) Road Erosion and Delivery Index (READI): a model for evaluating unpaved road erosion and stream sediment delivery. J Am Water Res Assoc 55:459–484. https://doi.org/10.1111/1752-1688.12729

Bonnin G, Martin D, Lin B, Parzybok T, Yekta M, Riley D (2006) Precipitation-frequency atlas of the United States - Puerto Rico and the U.S. Virgin Islands. NOAA Atlas 13

Carriger JF, Fisher WS, Stockton TB Jr, Sturm PE (2013) Advancing the Guánica Bay (Puerto Rico) Watershed Management Plan. Coast Manage 41:19–38. https://doi.org/10.1080/08920753.2012.747814

Collazo JA, Boulon R Jr, Tallevast TL (1992) Abundance and growth patterns of Chelonia mydas in Culebra, Puerto Rico. J Herpetol. https://doi.org/10.2307/1564884

Commonwealth of Puerto Rico and NOAA Coral Reef Conservation Program (2010) Puerto Rico's coral reef management priorities. NOAA, Silver Spring, MD

Cramer KL, O'Dea A, Leonard-Pingel JS, Norris RD (2020) Millennial-scale change in the structure of a Caribbean reef ecosystem and the role of human and natural disturbance. Ecography 43:283–293. https://doi.org/10.1111/ecog.04722

Cróquer A, Weil E (2009) Changes in Caribbean coral disease prevalence after the 2005 bleaching event. Dis Aquat Org 87:33–43. https://doi.org/10.3354/dao02164

Daly C, Helmer EH, Quiñones M (2003) Mapping the climate of Puerto Rico, Vieques, and Culebra. Int J Climatol 23:1359–1381. https://doi.org/10.1002/joc.937

Ewel JJ, Whitmore JL (1973) The ecological life zones of Puerto Rico and the U.S. Virgin Islands, United States Department of Agriculture, Institute of Tropical Forestry. Río Piedras, Puerto Rico

Gibbs DA, West JM, Bradley P (2021) Incorporating adaptation and resilience into an integrated watershed and coral reef management plan. PLoS ONE 16:e0253343. https://doi.org/10.1371/journal.pone.0253343

Gómez-Andújar NX, Hernandez-Delgado EA (2020) Spatial benthic community analysis of shallow coral reefs to support coastal management in Culebra Island, Puerto Rico. Peerj 8:e10080. https://doi.org/10.7717/peerj.10080

Goreau TJ, Cervino J, Goreau M, Hayes R, Hayes M, Richardson L, Smith G, DeMeyer K, Nagelkerken I, Garzon-Ferrera J, Gil D, Garrison G, Williams EH, Bunckley-Williams L, Quirolo C, Patterson K, Porter JW, Porter K (1998) Rapid spread of diseases in Caribbean coral reefs. Rev Biol Trop 46:157–171

Gould WA, Alarcón C, Fevold B, Jiménez ME, Martinuzzi S, Potts G, Quiñones M, Solórzano M, Ventosa E (2008) The Puerto Rico gap analysis project volume 1: Land cover, vertebrate species distributions, and land stewardship. United States Department of Agriculture, Forest Service, International Institute of Tropical Forestry, Río Piedras, Puerto Rico

Hernández-Delgado E (1992) Coral reef status of northeastern and eastern Puerto Rican waters: Recommendations for long-term monitoring, restoration and a coral reef management plan. Submitted to the Caribbean Fishery Management Council, Hato Rey. PR 87

Hernandez-Delgado EA, Alicea-Rodriguez L, Toledo CG, Sabat AM (2000) Baseline characterization of coral reefs and fish communities within the proposed Culebra Island marine fishery reserve, Puerto Rico. Proceedings of the Gulf and Caribbean Fisheries Institute. pp 537–555

Hernández-Delgado EA, Mercado-Molina AE, Suleimán-Ramos SE (2018) Multi-disciplinary lessons learned from low-tech coral farming and reef rehabilitation: I. Best management practices. In: Duque C, Tello Camacho E (eds) Proceedings of the coral in changing world. InTech Publications, Rijeka, Croatia, pp 213–244

Hernández-Delgado EA, Ramos-Scharrón CE, Guerrero-Pérez CR, Lucking MA, Laureano R, Méndez-Lázaro PA, Meléndez-Díaz JO (2012) Long-term impacts of non-sustainable tourism and urban development in small tropical islands coastal habitats in a changing climate: lessons learned from Puerto Rico. InTech Publications, Rijeka, Visions for Global Tourism Industry-Creating and Sustaining Competitive Strategies, pp 357–398

Irizarri Brugman EO, Bayouth García D, Hughes KS (2021) Widespread shallow mass wasting during Hurricane María: Long-term significance of sedimentation in the tropics. Rev Int Desast Nat Accide Infraest Civil 21:83–94

Jackson J, Donovan M, Cramer K, Lam V (2014) Status and trends of Caribbean coral reefs: 1970–2012. Global Coral Reef Monitoring Network, Gland, Switzerland

Jansma PE, Mattioli GS, Lopez A, DeMets C, Dixon TH, Mann P, Calais E (2000) Neotectonics of Puerto Rico and the Virgin Islands, northeastern Caribbean, from GPS geodesy. Tectonics 19:1021–1037. https://doi.org/10.1029/1999TC001170

Kastridis A (2020) Impact of forest roads on hydrological processes. Forests 11:1201. https://doi.org/10.3390/f11111201

Kitchell A, Kuchar B, Viqueira Ríos R (2021) Unpaved road standards for Caribbean and Pacific Islands. NOAA Restoration Center and Coral Reef Conservation Program, Silver Spring, MD

Larsen MC (2012) Landslides and sediment budgets in four watersheds in eastern Puerto Rico. In: Murphy S, Stallard RF (eds) Water quality and landscape processes of four watersheds in eastern Puerto Rico. pp 153–178

Larsen MC, Webb RM (2009) Potential effects of runoff, fluvial sediment, and nutrient discharges on the coral reefs of Puerto Rico. J Coast Res 25:189–208. https://doi.org/10.2112/07-0920.1

Larson RA, Brooks GR, Devine B, Schwing PT, Holmes CW, Jilbert T, Reichart G-J (2015) Elemental signature of terrigenous sediment runoff as recorded in coastal salt ponds: US Virgin Islands. Appl Geochem 63:573–585. https://doi.org/10.1016/j.apgeochem.2015.01.008

Loague KM, Freeze RA (1985) A comparison of rainfall-runoff modeling techniques on small upland catchments. Water Resour Res 21:229–248. https://doi.org/10.1029/WR021i002p00229

Luk S-h, Abrahams AD, Parsons AJ (1986) Methodology: a simple rainfall simulator and trickle system for hydro-geormophological experiments. Phys Geog 7:344–356. https://doi.org/10.1080/02723646.1986.10642303

MacDonald LH, Anderson DM, Dietrich WE (1997) Paradise threatened: land use and erosion on St. John, US Virgin Islands. Environ Manage 21:851–863. https://doi.org/10.1007/s002679900072

MacDonald LH, Sampson RW, Anderson DM (2001) Runoff and road erosion at the plot and road segment scales, St John, US Virgin Islands. Earth Surf Proc Landf 26:251–272. https://doi.org/10.1002/1096-9837(200103)26:3%3C251::AID-ESP173%3E3.0.CO;2-X

McLaughlin PW (2019) Impacts of unpaved roads on runoff and sediment production in Culebra, Puerto Rico. Masters Thesis. The University of Texas at Austin

Miller J, Muller E, Rogers C, Waara R, Atkinson A, Whelan KRT, Patterson M, Witcher B (2009) Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands. Coral Reefs 28:925–937. https://doi.org/10.1007/s00338-009-0531-7

Montañez Acuña AA (2022) Sostenibilidad financiera para el manejo estratégico de la Reserva Natural Canal de Luis Peña (2022–2031), Isla Municipio de Culebra, Puerto Rico. Masters Thesis. Universidad de Puerto Rico-Río Piedras

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models part I — a discussion of principles. J Hydrol 10:282–290. https://doi.org/10.1016/0022-1694(70)90255-6

Nemeth RS, Nowlis JS (2001) Monitoring the effects of land development on the near-shore reef environment of St. Thomas, USVI. Bull Mar Sci 69:759–775

Otaño-Cruz A, Montañez-Acuña AA, García-Rodríguez NM, Díaz-Morales DM, Benson E, Cuevas E, Ortiz-Zayas J, Hernández-Delgado EA (2019) Caribbean near-shore coral reef benthic community response to changes on sedimentation dynamics and environmental conditions. Front Mar Sci. https://doi.org/10.3389/fmars.2019.00551

Otaño-Cruz A, Montañez-Acuña AA, Torres-López V, Hernández-Figueroa EM, Hernández-Delgado EA (2017) Effects of changing weather, oceanographic conditions, and land uses on spatio-temporal variation of sedimentation dynamics along near-shore coral reefs. Front Mar Sci. https://doi.org/10.3389/fmars.2017.00249

Pagán-Villegas IM, Hernández-Delgado EA, Vicente VP (1999) Documento de designación Reserva natural del Canal de Luis Peña, Culebra, Puerto Rico. Departamento de Recursos Naturales y Ambientales, Programa de Manejo de la Zona Costanera de Puerto Rico, San Juan, PR

Ramos Scharrón CE (2021) Impacts of off-road vehicle tracks on runoff, erosion and sediment delivery–a combined field and modeling approach. Environ Model Softw 136:104957. https://doi.org/10.1016/j.envsoft.2020.104957

Ramos Scharrón CE, Alicea EE, Sanchez YF, LaFevor MC, McLaughlin P, MacDonald LH, Reale-Munroe K, Thomaz EL, Rios RV (2023) Three decades of road and trail runoff and erosion work in the Northeastern Caribbean–a research program perspective. J ASABE 66:35–45. https://doi.org/10.13031/ja.15078

Ramos Scharrón CE, Amador JM, Hernández-Delgado EA (eds) (2012) An interdisciplinary erosion mitigation approach for coral reef protection—a case study from the eastern Caribbean. Marine Ecosystems. InTech Publications, Rijeka, Croatia, pp 127–160

Ramos Scharrón CE, LaFevor MC (2016) The role of unpaved roads as active source areas of precipitation excess in small watersheds drained by ephemeral streams in the Northeastern Caribbean. J Hydrol 533:168–179. https://doi.org/10.1016/j.jhydrol.2015.11.051

Ramos Scharrón CE, LaFevor MC (2018) Effects of forest roads on runoff initiation in low-order ephemeral streams. Water Resour Res 54:8613–8631. https://doi.org/10.1029/2018WR023442

Ramos Scharrón CE, MacDonald LH (2007) Measurement and prediction of natural and anthropogenic sediment sources, St. John, US Virgin Islands. Catena 71:250–266. https://doi.org/10.1016/j.catena.2007.03.009

Ramos Scharrón CE, Thomaz EL (2017) Runoff development and soil erosion in a wet tropical montane setting under coffee cultivation. Land Degrad Dev 28:936–945. https://doi.org/10.1002/ldr.2567

Restrepo JD, Park E, Aquino S, Latrubesse EM (2016) Coral reefs chronically exposed to river sediment plumes in the southwestern Caribbean: Rosario Islands, Colombia. Sci Total Environ 553:316–329. https://doi.org/10.1016/j.scitotenv.2016.02.140

Roberts M, Hanley N, Williams S, Cresswell W (2017) Terrestrial degradation impacts on coral reef health: Evidence from the Caribbean. Ocean Coast Manage 149:52–68. https://doi.org/10.1016/j.ocecoaman.2017.09.005

Rogers CS, Ramos Scharrón CE (2022) Assessing effects of sediment delivery to coral reefs: a Caribbean watershed perspective. Front Mar Sci 8:773968. https://doi.org/10.3389/fmars.2021.773968

Soil-Survey-Staff (Undated) Web soil survey. Natural Resources Conservation Service, U.S. Department of Agriculture. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soil/citing-our-databases

Souter D, Planes S, Wicquart J, Logan M, Obura D, Staub F (2021) Status of coral reefs of the world: 2020: executive summary. Global Coral Reef Monitoring network (GCRMN) and International Coral Reef Initiative, p 19

Sturm P, Viqueira Ríos R, Ferguson R, Moore T (2012) Addressing land based sources of pollution in Guánica, Puerto Rico. In: 12th International Coral Reef Symposium. Cairns, Australia

Sturm P, Viqueira Ríos R, Meyer L, Hernández-Delgado EA, González-Ramos C, Montañez Acuña AA, Otaño-Cruz A, Ferguson R (2014) Culebra community watershed action plan for water quality and coral reefs. NOAA Coral Reef Conservation Program, Silver Spring, MD

Suchley A, Alvarez-Filip L (2018) Local human activities limit marine protection efficacy on Caribbean coral reefs. Conserv Lett 11:e12571. https://doi.org/10.1111/conl.12571

Viqueira Ríos R, Vandiver L, Kitchell A (2016) Reduction and control of sediment-laden runoff near critical coral reef ecosystems through the implementation of BMPs in Culebra, Puerto Rico- Final report. NOAA National Marine Fisheries Service, Silver Spring, MD

Virgen-Urcelay A, Donner SD (2023) Increase in the extent of mass coral bleaching over the past half-century, based on an updated global database. PLoS ONE 18:e0281719. https://doi.org/10.1371/journal.pone.0281719

Weil E, Croquer A, Urreiztieta I (2009) Temporal variability and impact of coral diseases and bleaching in La Parguera, Puerto Rico from 2003–2007. Caribb J Sci 45:221–246. https://doi.org/10.18475/cjos.v45i2.a10

Wemple BC, Browning T, Ziegler AD, Celi J, Chun KP, Jaramillo F, Leite NK, Ramchunder SJ, Negishi JN, Palomeque X (2018) Ecohydrological disturbances associated with roads: current knowledge, research needs, and management concerns with reference to the tropics. Ecohydrology 11:e1881. https://doi.org/10.1002/eco.1881

Winter A, Appeldoorn RS, Bruckner A, Williams EH Jr, Goenaga C (1998) Sea surface temperatures and coral reef bleaching off La Parguera, Puerto Rico (northeastern Caribbean Sea). Coral Reefs 17:377–382. https://doi.org/10.1007/s003380050143

Zar JH (1999) Biostatistical analysis. Pearson Education India, Delhi, India, p 663

Zhao Q, Wang A, Jing Y, Zhang G, Yu Z, Yu J, Liu Y, Ding S (2022) Optimizing management practices to reduce sediment connectivity between forest roads and streams in a mountainous watershed. Remote Sens 14:4897. https://doi.org/10.3390/rs14194897

Ziegler AD, Giambelluca TW (1997) Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand. J Hydrol 196:204–229. https://doi.org/10.1016/S0022-1694(96)03288-X

Ziegler AD, Negishi JN, Sidle RC, Gomi T, Noguchi S, Nik AR (2007) Persistence of road runoff generation in a logged catchment in Peninsular Malaysia. Earth Surf Proc Landf 32:1947–1970. https://doi.org/10.1002/esp.1508

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